

# Two-Higgs-doublet model with a color-triplet scalar: a joint explanation for top quark forward-backward asymmetry and Higgs decay to diphoton

Chengcheng Han<sup>1,2</sup>, Ning Liu<sup>1</sup>, Lei Wu<sup>2</sup>, Jin Min Yang<sup>2</sup>, Yang Zhang<sup>1</sup>

<sup>1</sup> *Physics Department, Henan Normal University, Xinxiang 453007, China*

<sup>2</sup> *State Key Laboratory of Theoretical Physics,  
Institute of Theoretical Physics, Academia Sinica, Beijing 100190, China*

## Abstract

The excess of top quark forward-backward asymmetry ( $A_{FB}^t$ ) reported by the Tevatron and the enhancement of the Higgs decay to diphoton observed by the LHC may point to a same origin of new physics. In this note we examined such anomalies in the two-Higgs-doublet model with a color-triplet scalar. We found that under current experimental constraints this model can simultaneously explain both anomalies at  $1\sigma$  level. Also, we examined the Higgs decay  $h \rightarrow Z\gamma$  and displayed its correlation with  $h \rightarrow \gamma\gamma$ . We found that unlike other models, this model predicts a special correlation between  $h \rightarrow Z\gamma$  and  $h \rightarrow \gamma\gamma$ , i.e., the  $Z\gamma$  rate is highly suppressed while the  $\gamma\gamma$  rate is enhanced. This behavior may help to distinguish this model in the future high luminosity run of the LHC.

PACS numbers: 14.65.Ha, 14.70.Pw, 12.60.Cn

## I. INTRODUCTION

Although the Standard Model (SM) agrees quite well with collider experiments, new physics is speculated to appear at TeV scale. If new physics beyond the SM indeed exist, it may readily affect the Higgs sector and the top quark sector. The reason is that the Higgs sector is responsible for electroweak symmetry breaking while the top quark is the heaviest fermion and sensitive to electroweak symmetry breaking. Actually, the top quark and Higgs boson entangled with each other, e.g., they couple 'strongly', the top quark loop dominates the Higgs production  $gg \rightarrow h$  and also sizably impact the clean decay  $h \rightarrow \gamma\gamma$ . So, the new physics (if really exist) may be simultaneously present in both sectors.

Luckily, we have seen anomalies from both the LHC Higgs data and the Tevatron top quark data. From the LHC Higgs data [1, 2] we see an enhancement in the diphoton channel while from the Tevatron top quark data [3] we see an excess for the top forward-backward asymmetry. Let's take a look at these anomalies:

- (i) For the Higgs boson, recently the ATLAS [1] and CMS [2] collaborations independently reported observation of a Higgs-like resonance around 125 GeV. Their observations are also supported by the Higgs search at the Tevatron [4]. Although the property of this Higgs-like boson is in rough agreement with the SM Higgs prediction, an excess at  $2\sigma$  level was observed in the diphoton channel [5, 6] and an enhancement in the  $Vb\bar{b}$  channel was also reported by the Tevatron [7].
- (ii) For the top quark, although most measurements at the Tevatron and LHC are well consistent with the SM predictions, an excess for the top quark forward-backward asymmetry ( $A_{FB}^t$ ) was observed by both CDF and D0 collaborations. For  $A_{FB}^t$  in the inclusive  $t\bar{t}$  production and in the high  $t\bar{t}$  invariant mass region ( $m_{t\bar{t}} > 450$  GeV), the deviations from the SM predictions [8] are about  $1.5\sigma$  and  $2.4\sigma$  respectively [3].

Although these anomalies are quite mild and may go away in the future, they stimulated various new physics explanations. The enhancement of the Higgs diphoton signal can be explained in the popular low energy supersymmetry (SUSY) [9] and other miscellaneous models (say with new scalars, new fermions or new vector bosons) [10–15] (note that the Higgs diphoton rate cannot be enhanced in some well-known new physics models like little Higgs theory and universal extra dimensions [16]). For the anomaly of  $A_{FB}^t$ , the popular

new physics models like SUSY cannot explain it while other strange models are tried to provide an explanation [17–20].

It is noteworthy that for the anomaly of  $A_{FB}^t$  a diquark model with a color anti-triplet scalar ( $\phi$ ) can provide a nice explanation [21] although it will inevitably lead to a color triplet resonance in the  $\bar{t}(t) + j$  system of the  $t\bar{t} + \text{jets}$  signature and thus highly constrained by the current data of top pair or single top production at the LHC [22, 23]. The intriguing point of this model is that the new predicted charged and colored scalar can also affect the processes  $gg \rightarrow h$  and  $h \rightarrow \gamma\gamma$  through the Higgs portal operator  $\phi^\dagger \phi H^\dagger H$  ( $H$  is the SM Higgs doublet) and may enhance the Higgs diphoton rate at the LHC. Actually, the effects of the general charged and colored scalars in the Higgs productions and decays have been studied in [24], where it is found that the scalars transforming as  $(8, 2, 1/2)$  and  $(\bar{6}, 3, -1/3)$  under the SM gauge group can improve the agreement with the Higgs data. Meanwhile, if the Higgs sector of the SM is also extended, such as in SUSY, a light color-triplet stop will be feasible for improving the fit of Higgs data [25]. So the extension of the Higgs sector may also play an important role.

In this note, we focus on the two-Higgs-doublet model with a new color anti-triplet scalar and examine the top quark forward-backward asymmetry and the Higgs diphoton decay. Under all available experimental constraints, we scan the parameter space to figure out if this model can provide a joint explanation for the anomalies of  $A_{FB}^t$  and Higgs decay to diphoton. Also, we will study the Higgs decay  $h \rightarrow Z\gamma$  and display its correlation with  $h \rightarrow \gamma\gamma$ .

This paper is organized as follows. In Sec. II, we briefly outline the relevant features of the diquark model. In Sec. III we examine the experimental constraints on the parameter space of the diquark model and then in the allowed parameter space we calculate  $h \rightarrow \gamma\gamma$ ,  $h \rightarrow Z\gamma$  and  $A_{FB}^t$ . Finally, we draw our conclusion in Sec. IV.

## II. A BRIEF DESCRIPTION OF THE MODEL

Motivated by the top quark forward-backward asymmetry, we consider a diquark model, in which the new scalar  $\phi$  transforms as  $(\bar{3}, 1, 4/3)$  under the gauge group  $SU(3)_C \times SU(2)_L \times U(1)_Y$  of the SM. Such a scalar can appear as a pseudo-Goldstone boson after the condensation of the fourth family fermions [26] or the condensation of the stop in SUSY with

large  $A_t$  term [27]. Compared with other diquarks with exotic quantum numbers, such as the color-sextet scalar, the color-triplet diquark is more favored by the measurement of  $t\bar{t}$  cross section because its interference with the SM processes is destructive [21]. After the electroweak symmetry breaking, the relevant Lagrangian of the color anti-triplet is given by [21]

$$\mathcal{L} \supset f_{ij}\bar{u}_{i\alpha}P_L u_{j\beta}^c \epsilon^{\alpha\beta\gamma}\phi_\gamma^\dagger + \text{h.c.} , \quad (1)$$

where  $f_{ij} = -f_{ji}$  with the indices  $i$  and  $j$  denoting the quark flavors,  $\epsilon^{\alpha\beta\gamma}$  is the antisymmetric tensor for the color indices  $\alpha, \beta, \gamma$ , and  $t^c$  is defined as  $t^c = C\bar{t}^T$  with  $C$  being the charge conjugate operator. In this model, since the main contribution to the process  $u\bar{u} \rightarrow t\bar{t}$  arises from flavor changing interaction between up quark and top quark, for simplicity, we can set the couplings  $f_{cu,ct} = 0$  to escape the constraints from low energy flavor physics like  $D^0 - \bar{D}^0$  mixing [21]. In this paper, we only use the low energy effective interaction of  $\phi$  and will not discuss the UV completion of this model. Therefore, we treat the coupling  $f_{ut}$  as a free parameter.

Another feature of this diquark model is that the color triplet scalar  $\phi$  can couple to the Higgs boson through the Higgs portal operator  $\phi^\dagger\phi H^\dagger H$ . In this work, considering the current Higgs data, we study the diquark in the framework of two-Higgs-doublet model, where the interaction between diquark and Higgs boson is given by [28]

$$V = m_\phi^2\phi^\dagger\phi + \kappa^2|\phi^\dagger\phi|^2 + \lambda^u\phi^\dagger\phi|H_u|^2 + \lambda^d\phi^\dagger\phi|H_d|^2 + (\lambda_M\phi^\dagger\phi H_d \cdot H_u + \text{h.c.}) \quad (2)$$

with  $H_u$  and  $H_d$  denoting the two Higgs doublets. After the electroweak symmetry breaking, the two Higgs doublets can be written as

$$H_d = \begin{pmatrix} v_d + (h_d + ia_d)/\sqrt{2} \\ H_d^- \end{pmatrix}, \quad H_u = \begin{pmatrix} H_u^+ \\ v_u + (h_u + ia_u)/\sqrt{2} \end{pmatrix}, \quad (3)$$

where  $v_u$  and  $v_d$  are the vacuum expectation values. Then we rotate these Higgs fields from the interaction eigenstates to the mass eigenstates:

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h_d \\ h_u \end{pmatrix} \quad (4)$$

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos \beta & \sin \beta \\ -\sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} H_d^\pm \\ H_u^\pm \end{pmatrix} \quad (5)$$

$$\begin{pmatrix} G^0 \\ A \end{pmatrix} = \begin{pmatrix} \cos \beta & \sin \beta \\ -\sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} a_d \\ a_u \end{pmatrix}, \quad (6)$$

where  $\tan \beta$  is defined as the ratio  $v_u/v_d$  and  $\alpha$  is the mixing angle between the two CP-even Higgs bosons. For simplicity, we assume  $\lambda^u = \lambda^d = \lambda$  and then obtain the interactions between the diquark and the light CP-even Higgs:

$$\begin{aligned} \lambda \phi^\dagger \phi |H_u|^2 + \lambda \phi^\dagger \phi |H_d|^2 &= \lambda \phi^\dagger \phi \left[ H_d^+ H_d^- + v_d^2 + \frac{1}{2}(h_d^2 + a_d^2) + H_u^+ H_u^- \right. \\ &\quad \left. + v_u^2 + \sqrt{2}(v_u h_u + v_d h_d) + \frac{1}{2}(h_u^2 + a_u^2) \right] \\ &\supseteq \sqrt{2} \lambda v \sin(\beta - \alpha) \phi^\dagger \phi h + \lambda v^2 \phi^\dagger \phi \end{aligned} \quad (7)$$

$$\begin{aligned} \lambda_M \phi^\dagger \phi H_d \cdot H_u + h.c. &= \lambda_M \phi^\dagger \phi (2v_u v_d + h_u h_d - a_d a_u + \sqrt{2}v_u h_d + \sqrt{2}v_d h_u \\ &\quad - H_u^+ H_d^- - H_d^+ H_u^-) \\ &\supseteq \sqrt{2} \lambda_M \cos(\beta + \alpha) v \phi^\dagger \phi h + \lambda_M v^2 \sin(2\beta) \phi^\dagger \phi \end{aligned} \quad (8)$$

Here we take the light CP-even Higgs boson as a SM-like Higgs boson. From Eqs.(7) and (8), we obtain the coupling of  $h\phi^\dagger\phi$ :

$$\mathcal{L}_{h\phi^\dagger\phi} = -\sqrt{2}v[\lambda \sin(\beta - \alpha) + \lambda_M \cos(\beta + \alpha)]h\phi^\dagger\phi. \quad (9)$$

Then in term of an effective coupling  $g_{h\phi\phi}$  and the diquark mass  $m_s$ , we can parameterize the above interaction as

$$\mathcal{L}_{h\phi^\dagger\phi} = -\sqrt{2}[\lambda \sin(\beta - \alpha) + \lambda_M \cos(\beta + \alpha)]v h\phi^\dagger\phi \equiv -g_{h\phi\phi} \frac{2m_s^2}{v} h\phi^\dagger\phi \quad (10)$$

where  $m_s^2 = m_\phi^2 + \lambda v^2 + \lambda_M v^2 \sin 2\beta$ . For the reduced couplings of Higgs boson with the vector bosons  $c_{hVV}$  ( $V = Z, W$ ) and fermions  $c_{hf\bar{f}}$ , they are same as in the general THDM:

$$c_{hVV} = \sin(\beta - \alpha), \quad c_{hbb} = -\frac{\sin \alpha}{\cos \beta}, \quad c_{ht\bar{t}} = \frac{\cos \alpha}{\sin \beta}. \quad (11)$$

In order to avoid the constraints from flavor physics and the LHC search for the non-standard Higgs bosons, we carry out the calculations in the decoupling limit  $m_A \gg m_Z$ . Therefore, the contribution of those non-standard Higgs bosons to the low energy observables is decoupled in our study.

### III. NUMERICAL RESULTS AND DISCUSSIONS

Due to the contributions of the new charged scalar, the decay widths of  $h \rightarrow gg$ ,  $h \rightarrow \gamma\gamma$  and  $h \rightarrow Z\gamma$  in the SM will be modified. In our case, the partial width of  $h \rightarrow \gamma\gamma$  can be expressed as [10]

$$\Gamma_{h \rightarrow \gamma\gamma} = \frac{G_\mu \alpha^2 m_h^3}{2\sqrt{2}\pi^3} |A(W - \text{loop}) + A(\text{top} - \text{loop}) + A(\text{diquark} - \text{loop})|^2 \quad (12)$$

where the amplitude functions are given by

$$\begin{aligned} A(W - \text{loop}) &= -\frac{7}{8} c_{hVV} A_v(\tau_W), \\ A(\text{top} - \text{loop}) &= \frac{2}{9} c_{ht\bar{t}} A_f(\tau_t), \\ A(\text{diquark} - \text{loop}) &= \frac{N(r_s)}{24} Q_s^2 g_{h\phi\phi} A_s(\tau_\phi) \end{aligned} \quad (13)$$

with  $\tau_i = m_i^2/4m_h^2$  ( $i = W, t, \phi$ ),  $N(r_s)$  being the dimension of the color representation of the new scalar and  $Q_s$  being its electric charge. For our model,  $N(r_s) = 3$  and  $Q_s = -4/3$ . The one-loop form factors are given by [29]

$$A_s(\tau) = \frac{3}{\tau^2} [f(\tau) - \tau], \quad (14)$$

$$A_f(\tau) = \frac{3}{2\tau^2} [(\tau - 1)f(\tau) + \tau], \quad (15)$$

$$A_v(\tau) = \frac{1}{7\tau^2} [3(2\tau - 1)f(\tau) + 3\tau + 2\tau^2], \quad (16)$$

$$f(\tau) = \begin{cases} \arcsin^2 \sqrt{\tau}, & \tau \leq 1; \\ -\frac{1}{4} [\log \frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi]^2, & \tau > 1. \end{cases} \quad (17)$$

The partial width of  $h \rightarrow gg$  is given by [10]

$$\Gamma_{h \rightarrow gg} = \frac{G_\mu \alpha_s^2 m_h^3}{36\sqrt{2}\pi^3} |A(\text{top} - \text{loop}) + A(\text{diquark} - \text{loop})|^2 \quad (18)$$

where the amplitude functions are

$$A(\text{top} - \text{loop}) = c_{ht\bar{t}} A_f(\tau_t), \quad (19)$$

$$A(\text{diquark} - \text{loop}) = \frac{1}{2} C(r_s) g_{h\phi\phi} A_s(\tau_\phi) \quad (20)$$

with  $C(r_s) = 1/2$  being the quadratic Casimir of the color representation of the diquark. At leading order, the cross section of  $gg \rightarrow h$  is directly related to the gluonic decay width  $\Gamma(h \rightarrow gg)$ :

$$\hat{\sigma}_{gg \rightarrow h} = \frac{\pi^2}{8m_h} \Gamma_{h \rightarrow gg} \delta(\hat{s} - m_h^2). \quad (21)$$

From Eqs.(12) and (14) we see that there are two ways to enhance the diphoton rate. One way is that the contribution of diquark is constructive to the  $W$ -loop, which needs a negative  $g_{h\phi\phi}$ . However, in this case, the main production process  $gg \rightarrow h$  will be highly suppressed and thus the Higgs data, especially for  $h \rightarrow VV^*$  [24] can hardly be accommodated. The other way is that the contribution of diquark is destructive to the  $W$ -loop. Then we need a large positive  $g_{h\phi\phi}$ . This will also enhance the production rate of  $gg \rightarrow h$ . We found this case to be consistent with the Higgs data by enhancing the decay width of  $h \rightarrow b\bar{b}$ , which is also needed to explain the observation of  $h \rightarrow b\bar{b}$  at Tevatron [7].

Note that, due to the gauge symmetry,  $h \rightarrow \gamma\gamma$  and  $h \rightarrow Z\gamma$  have a strong correlation in the SM. Therefore, the precise measurement of  $Z\gamma$  can help to understand the diphoton anomaly. The partial width of  $\Gamma_{h \rightarrow Z\gamma}$  is given by [10]

$$\Gamma_{h \rightarrow Z\gamma} = \frac{G_F^2 m_W^2 \alpha m_h^3}{64\pi^4} \left(1 - \frac{m_Z^2}{m_h^2}\right)^3 |A(W - \text{loop}) + A(\text{top} - \text{loop}) + A(\text{diquark} - \text{loop})|^2 \quad (22)$$

where the amplitude functions are

$$A(W - \text{loop}) = \cos \theta_W c_{hVV} \mathcal{C}_v(\tau_W, y_W^{-1}), \quad (23)$$

$$A(\text{top} - \text{loop}) = \frac{2 - (16/3) \sin^2 \theta_W}{\cos \theta_W} c_{ht\bar{t}} \mathcal{C}_f(\tau_t, y_t^{-1}), \quad (24)$$

$$A(\text{diquark} - \text{loop}) = -\sin \theta_W g_{Z\phi\phi} N(r_s) g_{h\phi\phi} \mathcal{C}_s(\tau_s, y_s^{-1}), \quad (25)$$

with  $y_i = m_Z^2/4m_i^2$  for  $i = W, t, \phi$  and  $g_{Z\phi\phi} = 2(T_\phi^3 - Q_s \sin^2 \theta_W)/\sin 2\theta_W$ . The loop functions are given by

$$\begin{aligned} \mathcal{C}_s(x, y) &= I_1(x, y), \\ \mathcal{C}_v(x, y) &= 4(3 - \tan^2 \theta_W) I_2(x, y) + ((1 + 2x^{-1}) \tan^2 \theta_W - (5 + 2x^{-1})) I_1(x, y), \\ \mathcal{C}_f(x, y) &= I_1(x, y) - I_2(x, y), \end{aligned} \quad (26)$$

where

$$\begin{aligned} I_1(x, y) &= \frac{xy}{2(x-y)} + \frac{x^2 y^2}{2(x-y)^2} (f(x^{-1}) - f(y^{-1})) + \frac{x^2 y}{(x-y)^2} (g(x^{-1}) - g(y^{-1})), \\ I_2(x, y) &= -\frac{xy}{2(x-y)} (f(x^{-1}) - f(y^{-1})), \\ g(x) &= \sqrt{x^{-1} - 1} \arcsin \sqrt{x}. \end{aligned} \quad (27)$$

In our study we consider the following experimental results about the top quark and Higgs boson from the LHC and Tevatron:

- (i) The cross section of  $t\bar{t}$  production: The CDF and CMS collaborations have measured the total  $t\bar{t}$  cross sections respectively [22, 31], which are in good agreement with the corresponding values predicted by the SM [32],

$$\begin{aligned}\sigma_{exp}^{t\bar{t},Tev} &= 7.50 \pm 0.31 \pm 0.34 \text{ pb}, & \sigma_{th}^{t\bar{t},Tev} &= 7.15_{-0.20-0.25}^{+0.21+0.30} \text{ pb}; \\ \sigma_{exp}^{t\bar{t},LHC} &= 161.9 \pm 2.5 \pm 3.6 \text{ pb}, & \sigma_{th}^{t\bar{t},LHC} &= 162.4_{-6.9-6.8}^{+6.7+7.3} \text{ pb}.\end{aligned}\quad (28)$$

In our calculations, we require the theoretical prediction (the SM value plus new physics effects) for the  $t\bar{t}$  total cross section to agree with the experimental data at  $2\sigma$  level.

- (ii) Top+jet resonance in  $t\bar{t}$ +jets events: In our model, the top quark can be produced in association with a diquark through new top flavor violating interactions. This will lead to a resonance in the top plus jet system of  $t\bar{t}$ +jets events when the diquark decays to  $\bar{t}q$ .

- Tevatron: The CDF Collaboration has recently searched for a  $t(\text{or } \bar{t})$ +jet resonance in  $t\bar{t}$ +jet events and set an upper limit of  $0.61 \sim 0.02$  pb for  $m_X = 200 \sim 800$  GeV [33].
- LHC: The similar search has been also carried out by the ATLAS collaboration at the LHC [34]. The measurement is consistent with the SM prediction and a color triplet scalar with mass below 430 GeV is excluded at 95% confidence level, assuming unit right-handed coupling. However, this bound can be released when the coupling become small.

- (iii) The charge asymmetry in  $t\bar{t}$  production at the LHC: The charge asymmetry in  $t\bar{t}$  production has been measured by the CMS [35] and ATLAS collaborations[36] in single lepton channel and is consistent with the SM prediction [37],

$$\begin{aligned}\sigma_{exp}^{t\bar{t},CMS} &= 0.004 \pm 0.010 \pm 0.012; \\ \sigma_{exp}^{t\bar{t},ATLAS} &= -0.024 \pm 0.016 \pm 0.023; \\ \sigma_{th}^{t\bar{t},LHC} &= 0.0115 \pm 0.0006\end{aligned}\quad (29)$$

We also require the new physics contribution plus the SM value to agree with the data at  $2\sigma$  level.



- (iv) The Higgs search data at the Tevatron and LHC: For different decay modes of Higgs boson, we define the following ratios of signal rate relative to the SM prediction:

$$\begin{aligned}
R_{VV^*}^{LHC} &\equiv \frac{\sigma(ggh + VBF)}{\sigma^{SM}(ggh + VBF)} \times \frac{Br(h \rightarrow VV^*)}{Br_{SM}(h \rightarrow VV^*)} \\
R_{\gamma\gamma}^{LHC} &\equiv \frac{\sigma(ggh + VBF)}{\sigma^{SM}(ggh + VBF)} \times \frac{Br(h \rightarrow \gamma\gamma)}{Br_{SM}(h \rightarrow \gamma\gamma)} \\
R_{Vbb}^{Tev} &\equiv \frac{\sigma(Vh)}{\sigma^{SM}(Vh)} \times \frac{Br(h \rightarrow b\bar{b})}{Br_{SM}(h \rightarrow b\bar{b})}
\end{aligned} \tag{30}$$

Here we do not use the LHC results of  $h \rightarrow \tau^+\tau^-$  due to the large uncertainty. We also note that an excesses in  $Vbb$  channel was also observed by the CMS collaboration, but its value was below the expectations for a SM Higgs boson at 125 GeV. So we only consider the measurement of  $Vbb$  at Tevatron [4, 7], which is  $R_{Vbb}^{Tev} = 1.97 + 0.74 - 0.68$ . For the observed Higgs boson with a mass of 125 – 126 GeV, the best fits to the signal rates are given by [38–40]

$$\begin{aligned}
R_{ZZ^*}^{ATLAS} &= 1.01 + 0.45 - 0.40, \quad R_{ZZ^*}^{CMS} = 0.81 + 0.35 - 0.28, \quad R_{ZZ^*}^{\text{combined}} = 0.88 \pm 0.25; \\
R_{WW^*}^{ATLAS} &= 1.35 + 0.57 - 0.52, \quad R_{WW^*}^{CMS} = 0.70 + 0.25 - 0.23, \quad R_{WW^*}^{\text{combined}} = 0.80 \pm 0.22; \\
R_{\gamma\gamma}^{ATLAS} &= 1.77 + 0.41 - 0.38, \quad R_{\gamma\gamma}^{CMS} = 1.56 + 0.46 - 0.42, \quad R_{\gamma\gamma}^{\text{combined}} = 1.68 \pm 0.29.
\end{aligned} \tag{31}$$

In our study, we require the theoretical predictions in our model to agree with the combined data at  $1\sigma$  level. We note that very recently, the CMS collaboration has measured  $h \rightarrow Z\gamma$  and set an upper limit on the production rate [30]. We also include this bound in our study.

In the numerical calculations, we take the SM parameters as [41]

$$m_t = 175 \text{ GeV}, \quad m_Z = 91.19 \text{ GeV}, \quad \sin^2 \theta_W = 0.2228, \quad \alpha = 1/128. \tag{32}$$

We use the parton distribution function CTEQ6m [42] with renormalization scale and factorization scale  $\mu_R = \mu_F = m_t$  for  $t\bar{t}$  production. We scan the parameters in the following ranges

$$\begin{aligned}
100 \text{ GeV} &< m_\phi < 500 \text{ GeV}, \quad 0.5 < f_{ut} < 1.2 \\
-10 &< g_{h\phi\phi} < 10, \quad -\frac{\pi}{2} < \alpha < \frac{\pi}{2}, \quad 5 < \tan \beta < 50.
\end{aligned} \tag{33}$$

Here the values of upper and lower bounds of  $m_\phi$  and  $f_{ut}$  are set to satisfy the latest search for top+jet resonance at the LHC [34]. For the coupling  $g_{h\phi\phi}$ , we find it can be as large as ten without conflicting with the unitarity constraints [43].

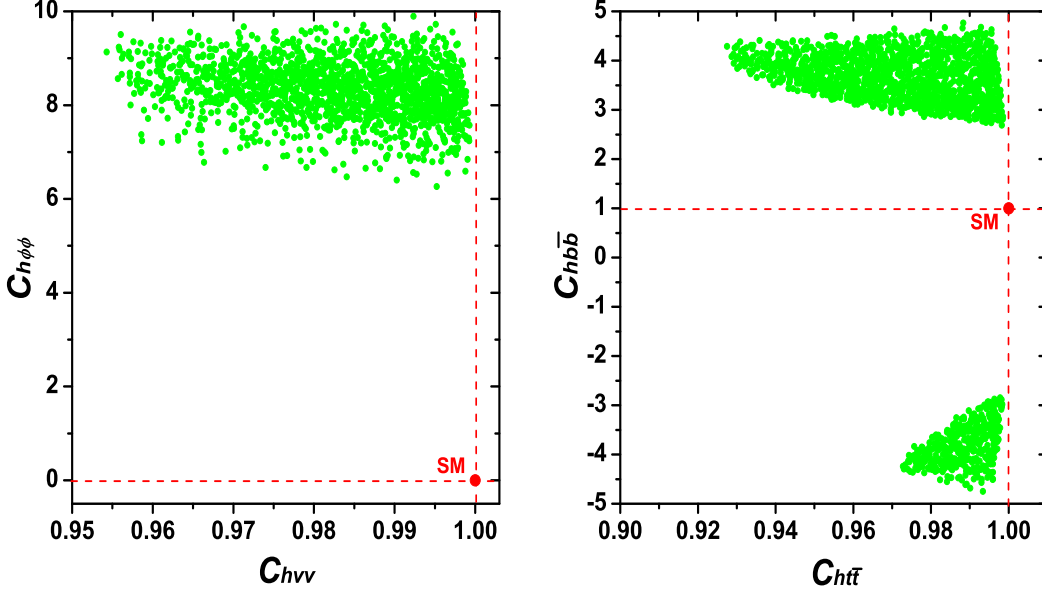


FIG. 1: The scatter plots of the parameter space allowed by the experimental constraints, projected on the planes of  $g_{h\phi\phi}$  versus  $c_{hVV}$  and  $c_{hb\bar{b}}$  versus  $c_{ht\bar{t}}$ . Here the couplings  $c_{hVV}$ ,  $c_{hb\bar{b}}$  and  $c_{ht\bar{t}}$  are normalized to the SM values.

In Fig.1, we project the samples that survive the experimental constraints (i)-(iv) on the planes of  $g_{h\phi\phi}$  versus  $c_{hVV}$  and  $c_{hb\bar{b}}$  versus  $c_{ht\bar{t}}$ . We see that the couplings  $c_{hVV}$  and  $c_{ht\bar{t}}$  in our model are very close to their SM values, but  $c_{hb\bar{b}}$  can be much larger than the SM value. This result is very different from the usual type-II THDM [44], where the diphoton rates are usually enhanced by reducing the  $hb\bar{b}$  coupling. It can also be seen that the samples with a positive  $c_{hb\bar{b}}$  can allow for a smaller  $c_{ht\bar{t}}$ . This is because the negative mixing angle  $\alpha$  can make the coupling of  $c_{hVV}$  larger and a small  $c_{ht\bar{t}}$  can suppress the production of  $gg \rightarrow h$  to make  $h \rightarrow VV^*$  consistent with the LHC data.

From Fig.1 we also see that the coupling  $g_{h\phi\phi}$  must be larger than 6.3 to meet the diphoton rates observed at the LHC. This can be understood from Fig.2, which shows the contribution of  $W$ -loop, top-loop and diquark-loop to the amplitude of  $h \rightarrow \gamma\gamma$  and  $h \rightarrow Z\gamma$ . We can see that the diquark-loop contribution to the amplitude of  $h \rightarrow \gamma\gamma$  is constructive to the top-loop but destructive to the  $W$ -loop. In order to enhance the diphoton rate, the diquark-loop should be dominant over the  $W$ -loop. We also note that with the increase of the diquark-loop, the  $W$ -loop and top-loop will be reduced by the couplings of  $c_{hVV}$  and

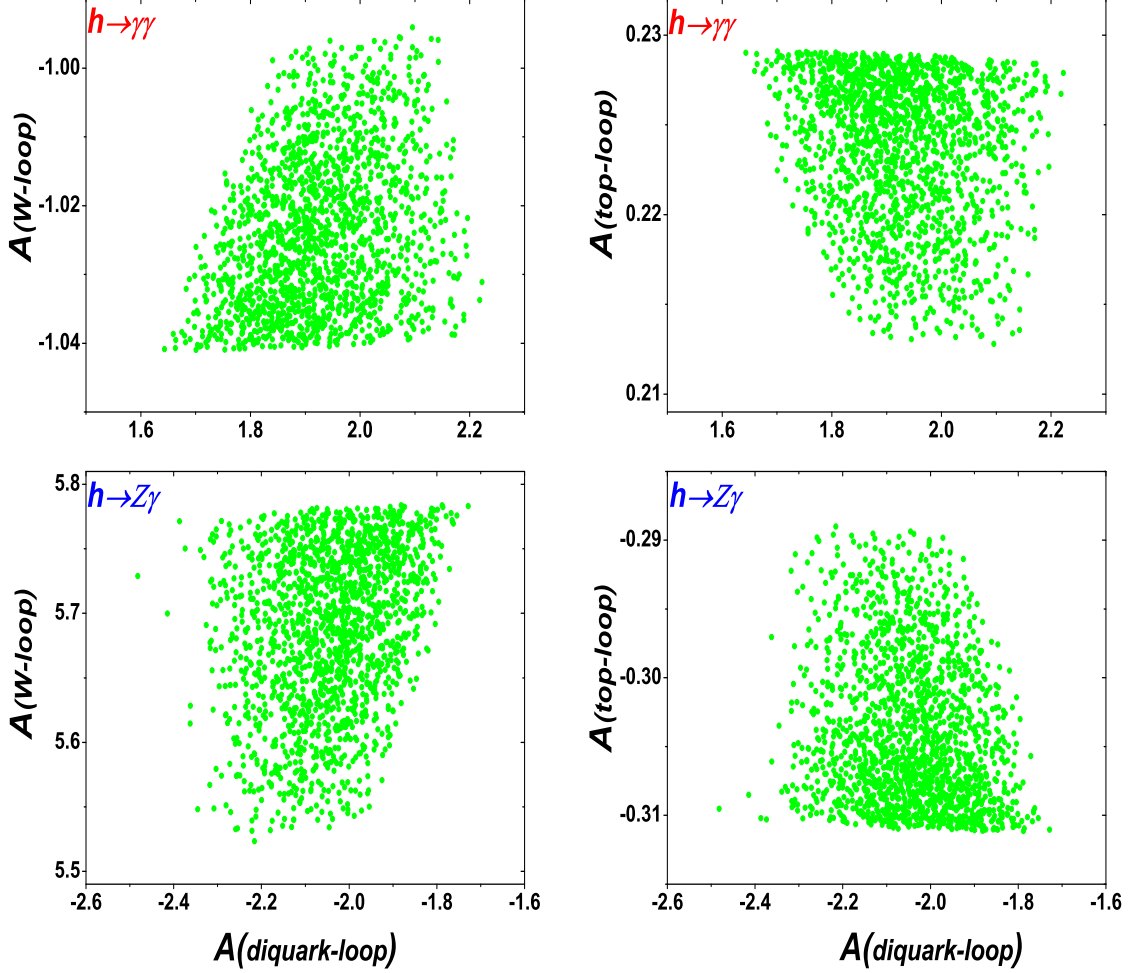


FIG. 2: Same as Fig.1, but showing the contribution of  $W$ -loop, top-loop and diquark-loop to the amplitude of  $h \rightarrow \gamma\gamma$  and  $h \rightarrow Z\gamma$ .

$c_{ht\bar{t}}$  so as not to cause excessive production of  $gg \rightarrow h \rightarrow VV$  at the LHC. For  $h \rightarrow Z\gamma$ , the diquark-loop has the same sign as the top-loop. But different from  $h \rightarrow \gamma\gamma$ , the  $W$ -loop contribution to the amplitude of  $h \rightarrow Z\gamma$  is always dominant even for a large  $g_{h\phi\phi}$ .

In Fig.3 we show the Higgs decay widths and their correlations. We can see that as the coupling  $g_{h\phi\phi}$  increases,  $\Gamma(h \rightarrow gg)$  and  $\Gamma(h \rightarrow \gamma\gamma)$  become large, which can maximally exceed the SM values by a factor of 12 and 3 respectively. But  $\Gamma(h \rightarrow Z\gamma)$  decreases and drops to 30% of the SM value when  $g_{h\phi\phi}$  goes up. These features lead to the different correlation behaviors, as shown in the below panel of Fig.3. The reasons for these features are two folds. One is that for a large  $g_{h\phi\phi}$  the diquark-loop is dominant in the decays  $h \rightarrow \gamma\gamma$

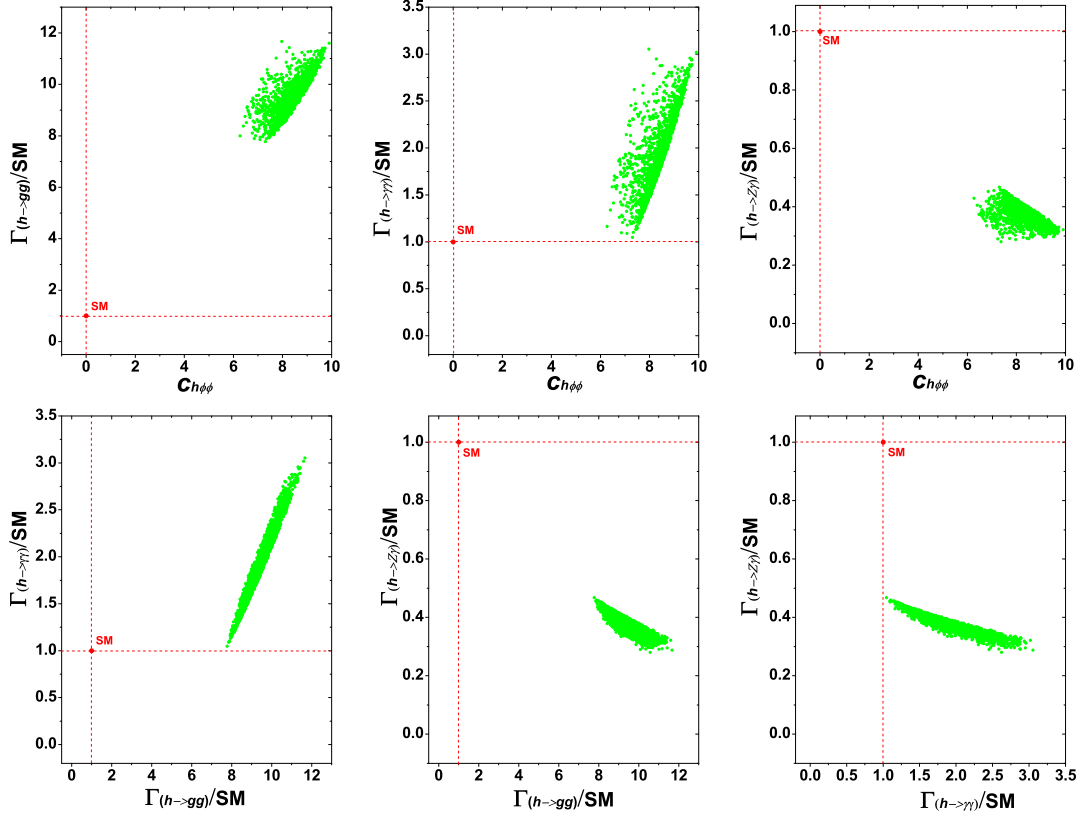


FIG. 3: Same as Fig.1, but showing the widths of  $\Gamma(h \rightarrow \gamma\gamma)$ ,  $\Gamma(h \rightarrow gg)$  and  $\Gamma_{Z\gamma}$  normalized to the SM values.

and  $h \rightarrow gg$ . Meanwhile, the sign of the diquark-loop is same as the top-loop so that it can greatly increase the width of  $h \rightarrow gg$  and  $h \rightarrow \gamma\gamma$  when  $g_{h\phi\phi}$  gets large. However, we should mention that the effect of a large  $\Gamma(h \rightarrow \gamma\gamma)$  on increasing the branch ratio  $Br(h \rightarrow \gamma\gamma)$  is limited, because the main partial width of  $\Gamma(h \rightarrow b\bar{b})$  is also enhanced by a large  $\tan\beta$ . Therefore, in our model the feasible way to increase the diphoton rates is to enhance the cross section of  $gg \rightarrow h$ . The other reason is that unlike the case in  $h \rightarrow \gamma\gamma$ , the diquark-loop in  $h \rightarrow Z\gamma$  can only cancel a small part of the contribution of  $W$ -loop. Thus, as  $g_{h\phi\phi}$  becomes large, the neat combined contribution to  $h \rightarrow Z\gamma$  gets smaller in magnitude.

Finally, in Fig.4 we show the results of  $A_{FB}^t$  at the Tevatron correlated with the LHC Higgs diphoton and  $Z$ -photon signal rates. The recent top quark measurement at the Tevatron gives  $A_{FB}^t = 15.0 \pm 5.5\%$  [3], which is larger than the SM prediction 0.056(7) [8]. Note that the diquark contributes to the  $t\bar{t}$  production through  $u$ -channel and will distort the

$t\bar{t}$  invariant mass distribution. The measurement of this  $t\bar{t}$  invariant mass distribution was performed by CDF [45] and ATLAS collaborations [46]. We require the new physics contribution in each bin to lie within the  $2\sigma$  range of the experimental values. However, because the shape of such a distribution in the high energy tail is sensitive to the cut efficiency of event selection and also sensitive to QCD corrections, we also show the results without considering the constraints from this distribution.

From Fig.4 we see that without the constraints of  $m_{t\bar{t}}$ , the prediction of  $A_{FB}^t$  at the Tevatron and the Higgs diphoton rate at the LHC can simultaneously lie in the  $1\sigma$  ranges of the experimental values. We also note that the  $Z\gamma$  rate of the Higgs is suppressed, below the half value of the SM prediction. Therefore, the measurement of  $Z\gamma$  rate will be useful for the test of our model.

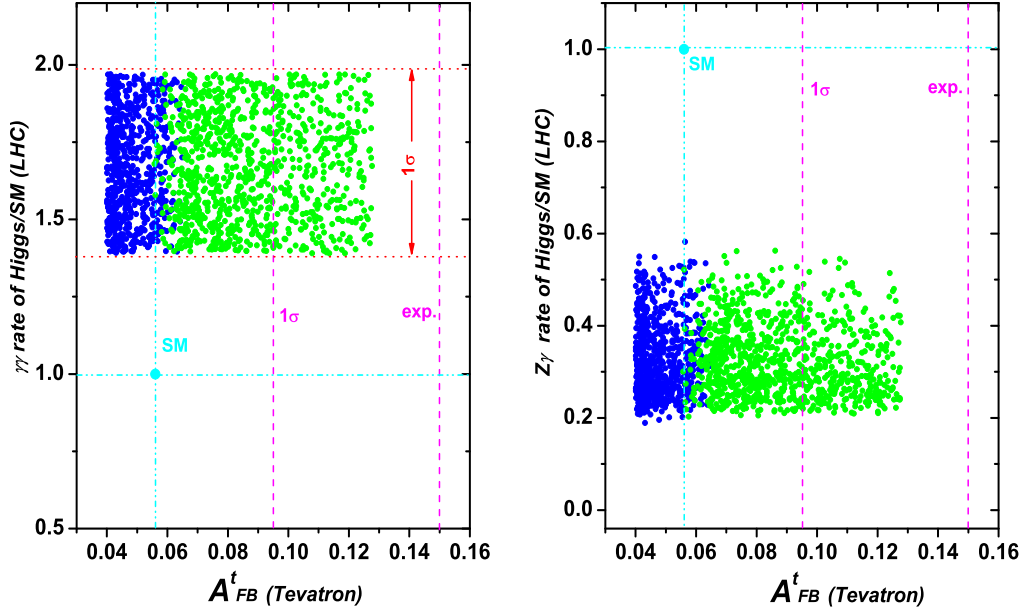


FIG. 4: Same as Fig.1, but showing the results of  $A_{FB}^t$  at the Tevatron correlated with the LHC Higgs diphoton and  $Z$ -photon signal rates. The bullets (blue) are the samples with the  $m_{t\bar{t}}$  constraints; while the times (green) are the samples without the  $m_{t\bar{t}}$  constraints.

## IV. CONCLUSION

In this paper we studied the Higgs boson decays to  $\gamma\gamma$  and  $Z\gamma$  and the top quark forward-backward asymmetry in a two-Higgs-doublet model with a color-triplet scalar. We found that under the current experimental constraints from the Higgs data and the top quark measurements, such a model can explain at  $1\sigma$  level the anomaly of the top quark forward-backward asymmetry observed by the Tevatron and the diphoton enhancement of the Higgs boson observed by the LHC. We also checked the correlation between  $h \rightarrow \gamma\gamma$ ,  $h \rightarrow Z\gamma$  and  $A_{FB}$  and found that the decay width of  $h \rightarrow Z\gamma$  will be highly suppressed due to the cancelation between diquark-loop and  $W$ -loop. Therefore, the future measurement of  $h \rightarrow Z\gamma$  at the LHC will help to test our model.

## Acknowledgement

We thank Prof. Junjie Cao for discussions. C. Han was supported by a visitor program of Henan Normal University, during which this work was finished. This work was supported in part by the National Natural Science Foundation of China under grant Nos. 11275245, 10821504 and 11135003, by the Project of Knowledge Innovation Program (PKIP) of Chinese Academy of Sciences under grant No. KJCX2.YW.W10. and by the Startup Foundation for Doctors of Henan Normal University under contract No.11112.

- 
- [1] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716**, 1 (2012).
  - [2] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716**, 30 (2012).
  - [3] T. Aaltonen *et al.* [CDF Collaboration], CDF note 10807; V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **84**, 112005 (2011).
  - [4] Tevatron New Physics Higgs Working Group and CDF and D0 Collaborations, arXiv:1207.0449.
  - [5] ATLAS Collaboration, ATLAS-CONF-2012-168.
  - [6] CMS Collaboration, CMS-PAS-HIG-12-015.
  - [7] T. Aaltonen *et al.* [CDF and D0 Collaborations], Phys. Rev. Lett. **109** (2012) 071804.

- [8] J. H. Kühn *et al.*, Phys. Rev. D **59**, 054017 (1999); M. T. Bowen *et al.*, Phys. Rev. D **73**, 014008 (2006); V. Ahrens *et al.*, JHEP **1009**, 097 (2010); arXiv:1106.6051; N. Kidonakis, arXiv:1105.5167. W. Bernreuther and Z. -G. Si, Nucl. Phys. B **837**, 90 (2010); W. Hollik and D. Pagani, arXiv:1107.2606.
- [9] The Higgs diphoton rate can be enhanced in some popular SUSY models, see, e.g., M. Carena *et al.* JHEP **1203**, 014 (2012); JHEP **1207**, 175 (2012); J. Cao *et al.*, JHEP **1210**, 079 (2012); JHEP **1203**, 086 (2012); Phys. Lett. B **710**, 665 (2012); Phys. Lett. B **703**, 462 (2011); U. Ellwanger, JHEP **1203**, 044 (2012); U. Ellwanger, C. Hugonie, arXiv:1203.5048; A. Arbey *et al.*, JHEP **1209**, 107 (2012); K. Hagiwara, J. S. Lee, J. Nakamura, JHEP **1210**, 002 (2012); R. Benbrik *et al.*, arXiv:1207.1096; T. Cheng, arXiv:1207.6392; B. Kyae, J.-C. Park, arXiv:1207.3126; H. An, T. Liu, L.-T. Wang, arXiv:1207.2473; J. Ke *et al.*, arXiv:1207.0990; G. Belanger *et al.*, arXiv:1208.4952; M. Drees, arXiv:1210.6507; S. F. King *et al.*, arXiv:1211.5074; K. Choi *et al.*, arXiv:1211.0875; M. Berg *et al.*, arXiv:1212.5009; L. Aparicio *et al.*, arXiv:1212.4808; C. Balazs, S. K. Gupta, arXiv:1212.1708; K. Cheung, C.-T. Lu, T.-C. Yuan, arXiv:1212.1288.
- [10] M. Carena, I. Low and C. E. M. Wagner, JHEP **1208**, 060 (2012).
- [11] A. Djouadi, Phys. Lett. B **435**, 101 (1998).
- [12] A. G. Akeroyd and S. Moretti, Phys. Rev. D **86**, 035015 (2012); A. Kobakhidze, arXiv:1208.5180. L. Wang and X. -F. Han, arXiv:1209.0376; M. Carena *et al.*, arXiv:1211.6136; E. J. Chun *et al.*, JHEP **1211**, 106 (2012); R. Sato *et al.*, Phys. Lett. B **716**, 441 (2012); W. -C. Huang and A. Urbano, arXiv:1212.1399; M. Chala, arXiv:1210.6208; I. Picek and B. Radovic, arXiv:1210.6449; E. O. Iltan, arXiv:1212.5695.
- [13] A. Joglekar *et al.*, arXiv:1207.4235; E. Bertuzzo *et al.*, arXiv:1209.6359; L. G. Almeida *et al.*, JHEP **1211**, 085 (2012); H. Davoudiasl *et al.*, arXiv:1211.3449; B. Batell *et al.*, arXiv:1211.2449; H. M. Lee *et al.*, arXiv:1209.1955; M. B. Voloshin, Phys. Rev. D **86**, 093016 (2012); N. Bonne and G. Moreau, Phys. Lett. B **717**, 409 (2012); S. Dawson and E. Furlan, Phys. Rev. D **86**, 015021 (2012); M. A. Ajaib, I. Gogoladze, Q. Shafi, arXiv:1207.7068; S. Dawson *et al.*, arXiv:1210.6663.
- [14] A. Alves *et al.*, Phys. Rev. D **84**, 115004 (2011); T. Abe, N. Chen and H. -J. He, arXiv:1207.4103.
- [15] A. Urbano, arXiv:1208.5782.
- [16] K. Hsieh and C.-P. Yuan, Phys. Rev. D **78**, 053006 (2008); L. Wang and J. M. Yang, Phys.

- Rev. D **84**, 075024 (2011); J. Reuter and M. Tonini, arXiv:1212.5930.
- [17] J. Cao *et al.*, Phys. Rev. D **81**, 014016 (2010). Q.-H. Cao *et al.*, Phys. Rev. D **81**, 114004 (2010); G. Rodrigo and P. Ferrario, Nuovo Cim. C **33**, 04 (2010); M. I. Gresham *et al.*, Phys. Rev. D **83**, 114027 (2011); J. F. Kamenik, J. Shu and J. Zupan, arXiv:1107.5257; S. Westhoff, arXiv:1108.3341.
- [18] P. Ferrario, G. Rodrigo, Phys. Rev. D **80**, 051701 (2009); JHEP **1002**, 051 (2010); P. H. Frampton *et al.*, Phys. Rev. D **683**, 294 (2010); M. V. Martynov, A. D. Smirnov, Mod. Phys. Lett. A **25**, 2637 (2010); R. S. Chivukula *et al.*, Phys. Rev. D **82**, 094009 (2010); Y. Bai *et al.*, JHEP **1103**, 003 (2011); A. Djouadi *et al.*, Phys. Rev. D **82**, 071702 (2010); K. Kumar *et al.*, JHEP **1008**, 052 (2010); M. Bauer *et al.*, JHEP **1011**, 039 (2010); J. Cao, L. Wu and J. M. Yang, Phys. Rev. D **83**, 034024 (2011); B. Xiao *et al.*, arXiv:1011.0152; C. H. Chen *et al.*, Phys. Lett. B **694**, 393 (2011); R. Foot, Phys. Rev. D **83**, 114013 (2011); A. Djouadi *et al.*, Phys. Lett. B **701**, 458 (2011); R. Barcelo *et al.*, arXiv:1105.3333; G. M. Tavares and M. Schmaltz, arXiv:1107.0978; E. Alvarez *et al.*, arXiv:1107.1473; E. Gabrielli and M. Raidal, arXiv:1106.4553; G. Z. Krnjaic, arXiv:1109.0648; U. Haisch, S. Westhoff, JHEP **1108**, 088 (2011); M. Cvetič *et al.*, JHEP **1211**, 064 (2012); S. S. Biswal *et al.*, arXiv:1211.4075; S. Dutta, A. Goyal and M. Kumar, arXiv:1209.3636; E. Gabrielli *et al.*, arXiv:1212.3272; A. Falkowski *et al.*, arXiv:1212.4003; M. Baumgart and B. Tweedie, arXiv:1212.4888; D. Barducci, S. De Curtis, K. Mimasu and S. Moretti, arXiv:1212.5948 [hep-ph].
- [19] S. Jung *et al.*, Phys. Rev. D **81**, 015004 (2010); Phys. Rev. D **83**, 114039 (2011). V. Barger *et al.*, Phys. Rev. D **81**, 113009 (2010); Phys. Lett. B **698**, 243 (2011); B. Bhattacharjee *et al.*, Phys. Rev. D **83**, 091501 (2011); K. M. Patel and P. Sharma, JHEP **1104**, 085 (2011); E. R. Barreto *et al.*, Phys. Rev. D **83**, 054006 (2011); arXiv:1104.1497; K. Blum *et al.*, arXiv:1107.4350; M. I. Gresham *et al.*, arXiv:1107.4364; N. Liu and L. Wu, Commun. Theor. Phys. **55**, 296 (2011); Y. Cui *et al.*, arXiv:1106.3086; M. Duraisamy, A. Rashed, A. Datta, arXiv:1106.5982; B. Grinstein *et al.*, arXiv:1108.4027; M. Frank *et al.*, arXiv:1108.0998; J. Cao *et al.*, Phys. Rev. D **84**, 074001 (2011); Phys. Rev. D **85**, 014025 (2012); E. L. Berger *et al.*, Phys. Rev. Lett. **106**, 201801 (2011); C. Han *et al.*, Phys. Lett. B **714**, 295 (2012); K. Yan *et al.*, Phys. Rev. D **85**, 034020 (2012); L. Wang *et al.*, Phys. Rev. D **85**, 075017 (2012); S. Knapen *et al.*, Phys. Rev. D **86**, 014013 (2012); V. Barger *et al.*, Phys. Rev. D **85**, 034016 (2012); P. Ko, Y. Omura and C. Yu, arXiv:1205.0407; D. Duffy *et al.*, Phys. Rev. D **85**, 094027



- (2012); L. Wang and X. -F. Han, JHEP **1205**, 088 (2012); E. Alvarez, Phys. Rev. D **86**, 037501 (2012); M. Dahiya *et al.*, arXiv:1206.5447; S. Y. Ayazi, arXiv:1207.0643; J. Adelman *et al.*, arXiv:1206.5731; S. Fajfe *et al.*, JHEP **1208**, 114 (2012); E. Alvarez and E. C. Leskow, Phys. Rev. D **86**, 114034 (2012); B. Yang and N. Liu, arXiv:1210.5120; M. Gonzalez-Alonso and M. J. Ramsey-Musolf, arXiv:1211.4581; E. Gabrielli *et al.*, arXiv:1212.3272; L. Basso *et al.*, JHEP **1209**, 024 (2012); L. Basso *et al.*, JHEP **1209**, 024 (2012); G. Belanger *et al.*, arXiv:1212.3526.
- [20] D. W. Jung *et al.*, Phys. Lett. B **691**, 238 (2010); arXiv:1012.0102; C. Zhang and S. Willenbrock, arXiv:1008.3869; J. A. Aguilar-Saavedra, Nucl. Phys. B **843**, 638 (2011); Nucl. Phys. B **812**, 181 (2009); C. Degrande *et al.*, arXiv:1010.6304; K. Blum *et al.*, arXiv:1102.3133; C. Delaunay *et al.*, arXiv:1103.2297; C. Degrande *et al.*, arXiv:1104.1798; J. A. Aguilar-Saavedra and M. Perez-Victoria, Phys. Lett. B **701**, 93 (2011); D. Y. Shao *et al.*, arXiv:1107.4012. S. S. Biswal *et al.*, Phys. Rev. D **86**, 014016 (2012); J. A. Aguilar-Saavedra *et al.*, arXiv:1209.6352; J. Drobnak *et al.*, Phys. Rev. D **86**, 054022 (2012); J. Drobnak *et al.*, arXiv:1209.4872.
- [21] J. Shu *et al.*, Phys. Rev. D **81**, 034012 (2010); I. Dorsner *et al.*, Phys. Rev. D **81**, 055009 (2010); A. Arhrib *et al.*, Phys. Rev. D **82**, 034034 (2010); Z. Ligeti *et al.*, JHEP **1106**, 109 (2011); K. Hagiwara and J. Nakamura, arXiv:1205.5005; B. C. Allanach and K. Sridhar, Phys. Rev. D **86**, 075016 (2012); G. Dupuis and J. M. Cline, arXiv:1206.1845.
- [22] S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1211** (2012) 067.
- [23] [ATLAS Collaboration], ATLAS-CONF-2012-096.
- [24] I. Dorsner, S. Fajfer, A. Greljo and J. F. Kamenik, arXiv:1208.1266.
- [25] For a light stop in SUSY and its phenomenology at the LHC, see, e.g., J. Cao *et al.*, JHEP **1211**, 039 (2012); M. R. Buckley and D. Hooper, Phys. Rev. D **86**, 075008 (2012); J. R. Espinosa *et al.*, arXiv:1207.7355; S. S. AbdusSalam and D. Choudhury, arXiv:1210.3331; R. T. D'Agnolo *et al.*, arXiv:1212.1165; Z. Kang *et al.*, arXiv:1208.2673; arXiv:1203.2336; X.-J. Bi, Q.-S. Yan, P.-F. Yin, arXiv:1111.2250; arXiv:1209.2703; arXiv:1211.2997.
- [26] B. Holdom, Phys. Lett. B **703** (2011) 576.
- [27] J. M. Cornwall, A. Kusenko, L. Pearce and R. D. Peccei, Phys. Lett. B **718** (2013) 951. A. Kusenko, V. Kuzmin and I. I. Tkachev, Phys. Lett. B **432** (1998) 361; G. F. Giudice and A. Kusenko, Phys. Lett. B **439** (1998) 55.

- [28] G. Chalons and F. Domingo, arXiv:1209.6235.
- [29] D. Carmi, A. Falkowski, E. Kuflik, T. Volansky and J. Zupan, JHEP **1210**, 196 (2012).
- [30] CMS Collaboration, CMS-PAS-HIG-12-049.
- [31] CDF results from <http://www-cdf.fnal.gov/>; V. M. Abazov et. al. [D0 Collaborations], arXiv:0903.5525.
- [32] M. Beneke, P. Falgari, S. Klein, J. Piclum, C. Schwinn, M. Ubiali and F. Yan, arXiv:1208.5578.
- [33] [http://www-cdf.fnal.gov/physics/new/top/confNotes/cdf10776\\_ttj.pdf](http://www-cdf.fnal.gov/physics/new/top/confNotes/cdf10776_ttj.pdf)
- [34] ATLAS Collaboration, ATLAS-CONF-2012-096.
- [35] CMS Collaboration, CMS-PAS-TOP-12-010.
- [36] ATLAS Collaboration, ATLAS-CONF-2011-106.
- [37] J. H. Kuhn and G. Rodrigo, JHEP **1201** (2012) 063.
- [38] ATLAS Collaboration, ATLAS-CONF-2012-162;
- [39] ATLAS Collaboration, ATLAS-CONF-2012-170;
- [40] CMS Collaboration, CMS-HIG-12-045;
- [41] C. Amsler *et al.*, Particle Data Group, Phys. Lett. B **667**, 1 (2008).
- [42] J. Pumplin *et al.*, Phys. Rev. D **82**, 074024 (2010).
- [43] A. Arhrib, hep-ph/0012353; A. G. Akeroyd *et al.*, Phys. Lett. B **490**, 119 (2000).
- [44] A. Drozd *et al.*, arXiv:1211.3580; G. Belanger *et al.*, arXiv:1212.5244; arXiv:1208.4952; P. M. Ferreira *et al.*, arXiv:1211.3131; Phys. Rev. D **85**, 035020(2012); Phys. Rev. D **85**, 077703(2012); Phys. Rev. D **86**, 015022(2012); S. Chang *et al.*, arXiv:1210.3439; S. Bar-Shalom *et al.*, arXiv:1208.3195; H. S. Cheon and S. K. Kang, arXiv:1207.1083; A. Arhrib *et al.* arXiv:1205.5536; Phys. Rev. D **85**, 095021(2012); C. -W. Chiang and K. Yagyu, arXiv:1207.1065; J. Chang *et al.*, arXiv:1206.5853; N. Chen and H. -J. He, JHEP **1204**, 062 (2012).
- [45] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **102**, 222003 (2009).
- [46] G. Aad *et al.* [ATLAS Collaboration], arXiv:1207.5644.